Energy Efficiency and Capacity Modeling for Cooperative Cognitive Networks

Rasool Sadeghi, João Paulo Barraca and Rui L. Aguiar

Instituto de Telecomunicações, Universidade de Aveiro, 3810-193 Aveiro, Portugal; e-mail: rsadeghi@av.it.pt, {jpbarraca, ruilaa}@ua.pt

Received 7 October 2011; Accepted: 19 April 2012

Abstract

Cooperative relaying has recently appeared as one of the widely recognized features for future wireless communication systems. The great potential of cooperative communication in increasing system capacity and enhancing power efficiency has attracted large efforts over the last few years. In this paper, we propose a Cooperation Loop as a reference model for all algorithms in relay based cooperative wireless networks. Using this model, we discuss cooperative relay based protocols in IEEE 802.11 standards and limits posed to cognitive approaches. We show the potential location area of relay nodes as well as the performance bounds of capacity gain, delay and power efficiency achieved in relay based scenarios for any cooperative cognitive algorithms.

Keywords: cooperation, cognitive, IEEE 802.11 MAC protocols, capacity, energy efficiency.

1 Introduction

Cooperative communications based on relay nodes have recently emerged as a novel approach in the design of next-generation wireless networks [1–8]. The classical paradigms of point-to-point and point-to-multipoint in wireless networks are being replaced by new interactions models, where the nodes cooperate with each other in order to improve the performance of their

Journal of Green Engineering, Vol. 2, 377–399.

own communication and of the global network. This aspect is of particular importance if done to maximize delivery under a varying environment, and employing cognitive techniques. The multipath propagation feature of the radio communication medium, long considered as the main reason of interference in conventional wireless networks, is now regarded as a potential resource for possible performance improvement in cooperative relay based networks, as well a source of potential energy reductions. In this concept, neighboring nodes overhear other messages and potentially help by relaying information. Cooperative relay communications address main challenges [2, 3, 9–12] in different types of wireless networks with the purpose of improving a given metric, such as overall system performance, or energy efficiency, by increasing capacity, survivability, range, and throughput, or simply transmission efficiency. One important aspect of cooperation is that cooperation is not always beneficial. Cognitive mechanisms must be used to evaluate the current environment and decide whether cooperation brings any improvement to network operation.

Recently, the topic of cognitive and cooperative networking has received significant attention from researchers, in particular when considering the IEEE 802.11 standard [13]. The IEEE 802.11 family of protocols arose as the dominant industrial standard for Wireless Local Area Networks (WLANs) providing simple mechanisms for the establishment of either infrastructure or ad-hoc networks. By allying cooperative and efficient cognitive schemes it is possible to devise promising solutions to improve the main features of the IEEE 802.11 standard, such as multiple transmission data rate adaptation and power control mechanisms. This highlights the potential practical role of cooperation to save the common network resources of power and spectrum. This work addresses this subject and has two major purposes: (1) To investigate the performance bounds of capacity gain obtained by cooperation in IEEE 802.11 networks, which can be used by a cognitive algorithm to decide when and how to cooperate, and (2) to assess power efficiency and power gain bounds of cooperative schemes in the best case scenario for cooperation, in such a way that can be explored in practical cognitive algorithms.

The rest of the paper is organized as follows: The concept of cooperation loop and the associated relevant parameters in IEEE 802.11 are described in Section 2. Section 3 discusses how cooperation can provide the solution for the main challenges in IEEE 802.11 MAC. Section 4 considers the mathematical methods to calculate the performance bounds of delay and capacity in IEEE cooperative relay based networks. In Section 5, we present a mathematical analysis evaluating the power gain and energy efficiency of relay based

MAC protocols, that can be incorporated in cooperative cognitive algorithms. Section 6 presents our simulation results, while Section 7 concludes the paper and presents future directions.

2 Solutions for Cooperative Communications

One of the main features of IEEE 802.11 WLAN is the support for multiple transmission data rates, which are related to the instantaneous conditions of the wireless channel, terminal capabilities, performance requirements, spectrum requirements, energy constrains, or simply administrative policies. Even though this feature increases the coverage area of wireless communication, it decreases the energy efficiency of the network, and leads to the problem called performance anomaly [14]: equal transmission opportunity provided to all involved nodes in the same IEEE 802.11 network leads to high latency required to complete the transmission of low data rate nodes, thus degrading the performance of the remaining, higher rate nodes. As an example, the duration time for the transmission of a packet of fixed size at the minimum data rate (6 Mbit/s), using the IEEE 802.11g protocol [15], makes the shared medium being occupied nine times longer when compared to the transmission the same packet at highest data rate (54 Mbit/s). This problem can be exacerbated in the most recent amendment of the standard, such as IEEE 802.11n [16], which supports up to 300 Mbit/s. Therefore the overall system performance is constrained by the ratio of low data rate nodes to all nodes in the same collision domain. Furthermore, the nodes at the edge of coverage area suffer from high packet loss rate due to worse channel conditions and higher interference levels. Cooperative protocols provide promising solutions to overcome these challenges of IEEE 802.11 networks. The key idea is that devices can sense their environment, and decide to replace one channel with bad conditions by two good channels. The meaning of bad and good channels depends on the purpose of the cooperation. As an example, in CoopMAC [17] and rDCF [18] one low data rate direct transmission link can be replaced by two faster transmission links, employing a relay node, yielding higher capacity. In other words, if the throughput improvement is the main of cooperation, the good channels are the ones that reduce the transmission delay. Interested readers can find proposals addressing this topic in [19–23].

The energy efficiency of the IEEE 802.11 MAC protocol is another important aspect of communications, especially for ad-hoc nodes powered by batteries and or other sources, such as solar panels. Therefore, efficient utilization of energy is a main concern of MAC protocol designers and the awareness to g green is now widely popular. Even though most of research works deal with throughput improvement gained by relay based MAC protocols, a few publications [17, 24–27] focus on the impact of relay nodes on the energy efficiency in cooperative relay based IEEE 802.11 networks. The authors of [24] demonstrated that cooperative relay schemes provides the power saving ranging from 7 to 20 dB over direct transmission and from 1 to 3 dB over multihop routes. It was observed in [17] that besides the network capacity gain by cooperative communications, energy efficiency gain is on the order of 20–40%. The energy efficiency of MIMO and cooperative MIMO systems were also investigated in [25] in which the authors address the issues such as energy cost and reduction of transmitter power in cooperative relay schemes. In addition, the authors in [26] demonstrate the energy efficiency of single relay cooperative MAC protocol while the results in [27] indicate the energy saving mechanism and energy performance improvement of multiple relay protocol when compared to normal IEEE 802.11 MAC protocol. Nevertheless, none of these works is able to provide a practical view of when to use cooperation, in the sense of a framework and rules guidelines that can be incorporated in the cognitive algorithms running on each node and that consider rate adaptation and energy efficiency simultaneously.

3 Cooperation in IEEE 802.11

Cognitive systems are able to adjust their operation according to changes in their environment. Therefore, similar to Autonomic Systems [28], cognitive systems make use of information sensed, which serves as feedback for future decisions. Our proposed Cooperation Loop can be structured as depicted in Figure 1, consisting of three phases: sense, decide and act. In this architectural reference model, the inception of cooperation is carried out, at each node, by sensing methods to sense the environment and neighbor nodes (Sense). The observation captured by the sense phase will be further used for a cognitive decision (Decide) when the cooperative strategies are determined based on cooperation policies, available sensing parameters and cooperation purposes. The final phase fulfills the cooperation procedure by sending the required control messages and initiating the cooperative transmission (Act). Different wireless communication environments such as Wireless LANs (WLANs), Wireless Sensor Networks (WSNs), Wireless Mesh Networks (WMNs), and Wireless Cellular Networks (WCNs) have particular requirements, which can be mapped to the operation of all states in this reference model. This cooper-

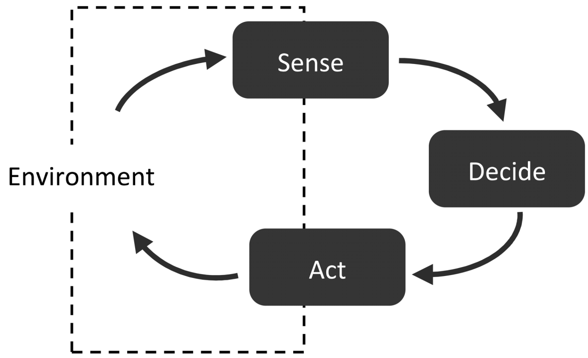


Figure 1 Feedback loop for the cooperative relay process.

ation loop concept can be applied for spectrum of features from channel level to network level and negotiating procedures within and across the OSI layers.

Since our study is focused on cooperation in the IEEE 802.11 family of standards, Table 1 summarizes different options for different cooperation loop phases. Some sensing parameters are achieved by overhearing the ongoing transmissions and extract the intended information explicitly from MAC header frames (e.g. RSSI [18]) or can be obtained by some computation based on overheard packets (e.g. data rate [12]). Moreover, sensing of some events such as packet failure and collision occurrence, can be another method to overhear the environment and initiate the cooperation if there are some possibilities. However, there are some protocols to exploit the cooperation by using upper layer features and cross layer approach: in [34], the priority of traffic flows is mapped in IEEE 802.11 MAC control packets and the overhearing nodes can sense the priority of ongoing packets and compare to their own priorities [34]. The Decision phase of cooperative MAC protocols includes parameters such as the number of employed relay(s) and a set of relay selection metrics. The Act phase determines which node(s) can initiate the cooperation and how the control mechanism and notification signaling are applied. This spectrum of parameters can be used by a myriad of cognitive algorithms for cooperative communication, combined differently depending on the overall system objectives. In the scope of cognitive networks, sensed information and past decisions can also be used to make future decisions, or to other control layers (The set of sensed parameters can include information from applications. In particular, what delivery requirements they have, or what type of power source is available.)

Table 1 Summary of cooperation loop in IEEE 802.11.

Sensing	Decision	Act		
Type	Relay selection metric	Initiation	Control	Notification
RSSI [19] PLCP header [18] Packet Failure [32] Data rate [30] Collision occurrence [12] Priority of traffic flow [34]	Max. data rate [18] Random [32] Priority based [35] Service differentiation [34]	Source [19] Relay [36] Source-Relay [35]	Centralized [18] Distributed [19] Hybrid [36]	CFC Message [32]

Unlike simple cognitive radio communications [29] which are based on spectrum sensing, and reconfigurable capabilities, we propose the usage of cooperation loop as a modular framework, able to support different cooperative cognitive protocols for existing IEEE 802.11 networks, according to the best interest of a particular network or individual nodes. Depending on the main purpose of cooperation, we can select one or some of the sensing parameters listed in Table 1 and then we can create a composite metric. By using this metric the decider node determines which set(s) of nodes can participate in cooperation and also estimates which set of source, destination and relay(s) can be more beneficial for a particular traffic. In the Act phase of cooperation loop there are spectrum of features including the initiation, signaling and control plan for a cooperative cognitive process. In some of these phases, we can also exploit opportunistic schemes instead of deterministic ones [30].

4 Delay Performance and Capacity Gain in Cooperative IEEE 802.11

In order to improve the throughput in cooperative IEEE 802.11 network using relay nodes, the transmission delayshould often considered as the main metric to initiate the cooperation process. Transmission delay is the time a data packet takes to be transmitted over the medium. So we should have a practical sensing method to obtain the transmission delay of direct and relay paths. For instance, for given three nodes as depicted in Figure 2, node R as a potential relay can explicitly obtain the actual data rate achieved between Access Point(AP) and $N(k)$ from overhearing data frames exchanged between node (AP) and N. The IEEE 802.11 MAC header (or in more detail, the PLCP sub-header), contains a field named SIGNAL, which denotes the bit rate of

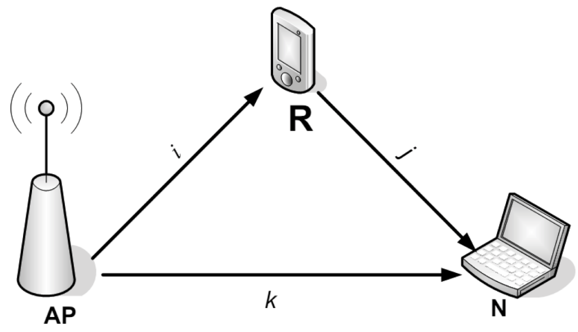


Figure 2 Cooperative scenario using relay node in infrastructure WLAN.

every data packet sent to the network. Node R can also discover the potential bitrates between itself and $AP(i)$ and $N(j)$. For that, node R measures the Received Signal Strength Indication (RSSI) of RTS and CTS frames issued by the AP and N and computes the corresponding data rates of obtained RSSI(s). After obtaining the three data rates between these three nodes (Sense phase), we can define a metric such as Delay Ratio (DR) [33]. Delay ratio is the ratio between the transmission delay of relay path, and that of the direct path (Decide phase) and can be expressed as

$$DR_{ijk} = \frac{i^{-1} + j^{-1}}{k^{-1}} \tag{1}$$

when the relay node supports data rates of i Mbit/s and j Mbit/s to AP and node N respectively and the direct transmission data rate between AP and node N is k Mbit/s. In this paper, we focus on the bounds of MAC layer performance with high data packet size and we ignore the MAC overhead. It is noted that the accurate value of delay ratio should include the overhead and it depends on the specific cooperation technique. Clearly, if the value of the calculated delay ratio is less than 1, the relay channel will possibly provide better transmission characteristics than the direct channel, due to the resulting higher bandwidth and lower transmission delay for end-to-end communication. Note that in this first approximation, the processing delay in node R and access delay are neglected. In addition, in order to consider the capacity improvement corresponding to the obtained delay ratio, we define the Cooperative Capacity (CC) as

$$CC_{ijk} = k\frac{i^{-1} + j^{-1}}{k^{-1}} \tag{2}$$

Table 2 Delay ratio less than 1 and equivalent cooperative capacity for IEEE 802.11b.

DELAY RATIO	AP to N Data rate (Mbit/s)	AP to R Data rate (Mbit/s)	R to N Data rate (Mbit/s)	Cooperative capacity (Mbit/s)
0.18	1	11	11	5.5
0.27	1	11	5.5	3.7
0.36	1	5.5	5.5	2.8
0.59	1	2	11	1.7
0.68	1	2	5.5	1.5
0.36	2	11	11	5.6
0.54	2	11	5.5	3.7
0.72	2	5.5	5.5	2.8
1	5.5	11	11	5.5
2	11	11	11	5.5

Table 2 shows all delay ratio values less than 1 and equivalent cooperative capacity obtained by cooperative relay based communication in scenario of Figure 2 using IEEE 802.11b (the table is limited to IEEE 802.11b for simplification). The best performance for cooperation occurs when delay ratio is minimal, in this case 0.18, and provides a reduction in delay of around 72%, considering that the direct data rate is 1 Mbit/s, and the data rate between source to Figure 2 Cooperative scenario using relay node in infrastructure WLAN relay and relay to destination is 11 Mbit/s. As it can be observed, the usefulness of using a relay decreases, when the data rate between AP and N increases. Table 2 shows that relay selection algorithms are only useful when end-to-end data rate is near the lower limits allowed by the standard. For instance, in the IEEE 802.11b standard if the data rate between AP and N is 5.5 Mbit/s or 11 Mbit/s, no cooperation leading to a reduction in delay will be possible. This is a practical rule that any cognitive algorithm for IEEE 802.11b should incorporate.

One of the main questions in cooperative relay based wireless networks is which percentage of the access point coverage area can potentially improve the performance corresponding to obtained delay ratio. Another important point of concern is what are the performance bounds (minimum, maximum) and expected average of delay ratio and capacity gain achieved by cooperative schemes in the different data rates supported by IEEE 802.11 family of protocols. In the rest of this section, we will answer these questions by proposing a mathematical model for delay and area analysis.

The relay nodes can perceive the various values of delay ratio due to different data rates supported in IEEE IEEE 802.11. The area wherein every

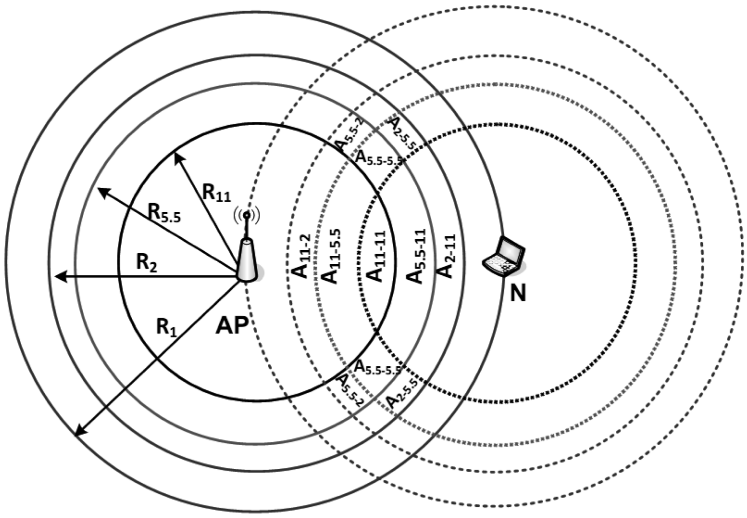


Figure 3 Relay area for direct transmission of 1 Mbit/s.

relay node can move while its delay ratio does not change is called relay area. To obtain the relay area versus delay ratio, we consider the geometric model of cooperation. As depicted in Figure 3, an infrastructure WLAN includes node N which is located at the transmission range of R_1 to support 1 Mbit/s data rate to AP. The intersection area of A_{ijk} denotes the potential area for relay node corresponding to DR_{ijk} discussed in (1). To obtain the $A_{ijk}'s$, we consider the overlap area of two circles with radii of r_1 and r_2 and distance of l between their centers. The overlap area, denoted by S_{r1r2} can be written as

$$S_{r1r2} = {r_1}^2 \sin^{-1}(h/r_1) + {r_2}^2 \sin^{-1}(h/r_2) - hl \tag{3}$$

where

$$h = \frac{\sqrt{2{r_1}^2{r_2}^2 + 2({r_1}^2 + {r_2}^2)l^2 - ({r_1}^4 + {r_2}^4) - l^4}}{2l}$$

The relay area is not covered directly by calculated overlap area, but the relation between this overlap area of two circles and relay area of $A_{ijk}'s$ in Figure 3 can be easily calculated as Equation (4). The value of k is equal to 1 because of direct transmission data rate of 1 Mbit/s between AP and N in Figure 3. Table 3 summarizes all relay area and corresponding delay ratio

Table 3 Delay ratio of different relay area for direct transmission of 1 Mbit/s.

Relay area	$A_{11-11-1}$	$A_{11-5.5-1}$	$A_{5.5-5.5-1}$	A_{11-2-1}	$A_{5.5-2-1}$
Delay ratio	0.18	0.27	0.36	0.59	0.68

values.

$$\begin{cases} A_{11-11-1} = S_{R_{11}R_{11}} \\ A_{11-5.5-1} = A_{5.5-11-1} = S_{R_{11}R_{5.5}} - S_{R_{11}R_{11}} \\ A_{11-2-1} = A_{2-11-1} = S_{R_{11}R_2} - S_{R_{11}R_{5.5}} \\ A_{5.5-5.5-1} = (S_{R_{5.5}R_{5.5}} - S_{R_{11}R_{5.5}} - A_{11-5.5-1})/2 \\ A_{5.5-2-1} = A_{2-5.5-1} = (S_{R_{5.5}R_2} - S_{R_{5.5}R_{5.5}} - A_{2-11-1})/2 \end{cases} \tag{4}$$

As shown in Table 3, and considering the data rates available in IEEE 802.11, a single value of delay ratio is present in each relay area. Delay performance improvement for every direct transmission of k Mbit/s can be expressed as Average Weighted Delay Ratio (AWDR):

$$AWDR_k = \frac{\sum_i \sum_j A_{ijk}\overline{DR_{ijk}}}{\sum_i \sum_j A_{ijk}} \tag{5}$$

where

$$\overline{DR} = \{DR | DR_{ijk} < 1\} \tag{6}$$

In addition, we need to define some performance bounds of lower and upper of delay ratio given by

$$\text{Lower Bound of Delay Ratio } (LBDR_k) = \min\{\overline{DR}\} \tag{7}$$

$$\text{Upper Bound of Delay Ratio } (UBDR_k) = \max\{\overline{DR}\} \tag{8}$$

As depicted in Table 2, the value of k should be 1 Mbit/s and 2 Mbit/s in IEEE 802.11b to satisfy the $DR_{ijk} < 1$. Similar to delay performance, we can define the metrics of (AWCC) to (UBCC) respectively for average, minimum and maximum of cooperative capacity.

$$AWCC_k = \frac{\sum_i \sum_j A_{ijk}\overline{CC_{ijk}}}{\sum_i \sum_j A_{ijk}} \tag{9}$$

$$\text{Lower Bound of Cooperative Capacity } (LBCC_k) = \min\{\overline{CC}\} \tag{10}$$

$$\text{Upper Bound of Cooperative Capacity } (UBCC_k) = \max\{\overline{CC}\} \tag{11}$$

where

$$\overline{CC} = \left\{ CC | CC_{ijk} = \frac{1}{DR_{ijk}} \text{ and } DR_{ijk} < 1 \right\} \tag{12}$$

In Section 4, we present the relay area based on delay ratio for different revisions of IEEE 802.11. We also consider the average value, lower and upper bound of delay and capacity performance for different direct transmission data rates.

5 Power Performance and Energy Efficiency in Cooperative IEEE 802.11

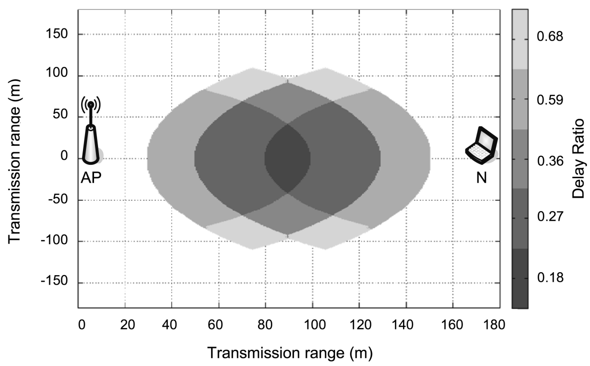
Energy efficiency in networks using IEEE 802.11 is affected by factors such as the transmit power used and the processing power required for forwarding packets by mobile nodes. Evaluating how throughput varies with the use of relays is important because it allows to also study the resulting energy efficiency. In a non-cooperative direct transmission, the power allocation is carried out only by the source node, while in a cooperative scenario both source and relay nodes should allocate power to complete the transmission. The source node requires power to transmit the packet to the relay, while the relay requires power to forward the packet to the destination. Due to the multi-rate nature of IEEE 802.11, source nodes must collect information from other nodes and reason over it. This way they are able to take an informed decision in whether to send packets through a relay, or directly to the destination. For a direct transmission in the scenario depicted in Figure 4(a), the average received power can be expressed (in dBm) as:

$$P_{r_D} = P_{r_D} + G_t + G_r - PL_d \tag{13}$$

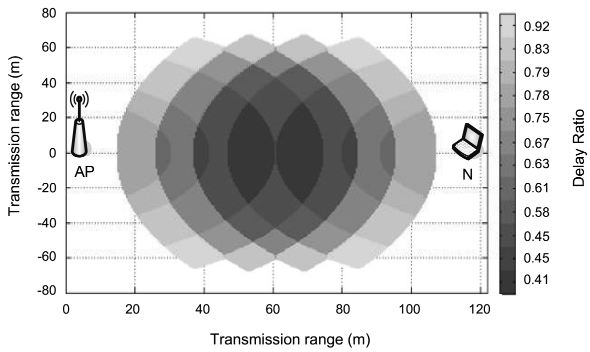
where P_{r_D} (in dBm) is the power radiated by the source in a direct transmission, G_t and G_r are the transmitter and receiver antenna gains, respectively, and PL_d the path loss in dB between source and destination. Considering isotropic antennas, $G_t = G_r = 0$ dBi and the path loss is given by [31]:

$$PL(d) = PL(d_0) + 10n \log_{10} \frac{d}{d_0} \tag{14}$$

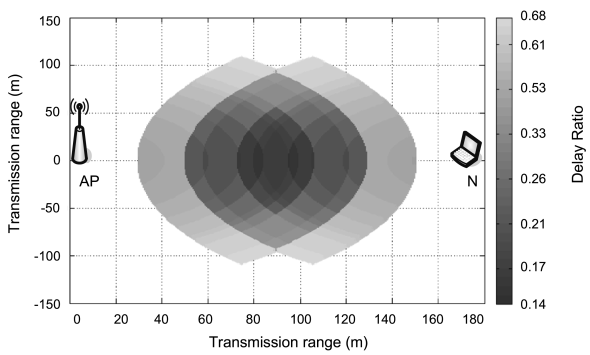
where $PL(d_0)$ is the path loss at $d_0 = 1$ m, and $PL(d_0) = -20 \log_{10}(c/4\pi f d_0) = 40.2$ dB at 2.4 GHz, d is the distance between transmitter and receiver and n is the path loss coefficient. For indoor environments with obstructions, such as inside buildings, the path loss coefficient is



(a)



(b)



(c)

Figure 4 Relay area versus delay ratio for end to end direct transmission of (a) 1 Mbit/s-IEEE 802.11b, (b) 6 Mbit/s-IEEE 802.11g and (c) 1 Mbit/s-IEEE 802.11bg.

between 4 and 6 [31]. The SNR of the received signal for the power noise of N_0 can be expressed as (SNR_d):

$$SNR_d = P_{r_D} - N_0 = P_{t_D} + G_t + G_r - PL_D - N_0 \tag{15}$$

In a cooperative communication for the same scenario (Figure 4(b)), the average power received by the relay and destination nodes, and the SNR of the received signal can be given by

$$Pr_{rly} = Pt_S + G_t + G_r - PL(d_1) \tag{16}$$

$$Pr_{Dst} = Pt_R + G_t + G_r - PL(d_2) \tag{17}$$

$$SNR_{Rly} = P_{Rly} - N_0 = Pt_S + G_t + G_r - PL(d_1) - N_0 \tag{18}$$

$$SNR_{Dst} = P_{Dst} - N_0 = Pt_R + G_t + G_r - PL(d_2) - N_0 \tag{19}$$

Obviously, the symmetric cooperative scenario can provide the energy efficiency when $PL(d_1)$ and $PL(d_2)$ are minimum and the conditions of Equation (20) are satisfied.

$$d_1 = d_2 and Pt_S = Pt_R \tag{20}$$

and by substituting Equation (20) into (18):

$$Pr_{rly} = Pr_{Dst} = Pt_S + G_t + G_r - PL(d/2) \tag{21}$$

In order to express the power gain, we define the ΔP as

$$\Delta P = Pr_D - Pr_{Rly} = Pt_D - Pt_S - PL(d) + PL(d/2) \tag{22}$$

ΔP can be expressed as

$$\Delta P = SNR_D - SNR_{Rly} \tag{23}$$

$$\begin{cases} \Delta P & = SNR_D - SNR_{Rly} \\ \Delta P & = Pt_D - Pt_S - PL(d) + PL(d/2) \\ & = Pt_D - Pt_S - 10n \log_{10} 2 \\ & = Pt_D - Pt_S - 3n \end{cases} \tag{24}$$

Substituting (23) into (24) yields

$$SNR_D - SNR_{Rly} = Pt_D - Pt_S - 3n \tag{25}$$

The possible values for the medium path loss coefficient n and minimum SNR, required to support the corresponding data rates in IEEE 802.11

Table 4 Data and transmission ranges of IEEE 802.11bg.

IEEE 802.11g	Data rate (Mbit/s)	6	9	12	18	24	36	48	54
	Typical Range (meter)	122	107	96	85	75	61	42	31
	Min-SNR (dB)	8	9	11	13	16	20	24	25
IEEE 802.11b	Data rate (Mbit/s)	1	2	5.5	11				
	Typical Range (meter)	180	150	130	100				
	Min-SNR (dB)	2	2.9	5.4	10				

standard can determine the range of $(Pt_D - Pt_S)$. Let us suppose $SNR_D - SNR_{Rly} = \beta$ and SNR_D and SNR_{Rly} provide the symmetric and delay ratio ≈ 1. Therefore,

$$Pt_D - Pt_S = \beta + 3n \tag{26}$$

It can be easily concluded that the final power gain is

$$PG = Pt_D - Pt_S - 3 \tag{27}$$

The value of 3dB is related to symmetric scenario and equal allocated power in source and relay of cooperative scenario. Thus,

$$PG = \beta + 3(n - 1) \tag{28}$$

In the next section, we will demonstrate how the range of n can determine the minimum and maximum value of PG.

6 Simulation and Results

In order to evaluate the delay performance, capacity performance and energy efficiency of cooperative transmissions as discussed in the previous sections, we devised a scenario with two nodes communicating by using IEEE 802.11bg, and then obtain the maximum distance and the minimum SNR required for maintaining all data rates supported by IEEE 802.11b and IEEE 802.11g. Table 4 indicates the data rates achievable at the different transmission ranges, and the minimum SNR required for $BER < 10^{-5}$: as expected, as the distance between any two nodes increases, the data rates will be adapted down. IEEE 802.11g supports between 54 and 6 Mbit/s, while IEEE 802.11b supports rates between 1 and 11 Mbit/s.

An important aspect of this analysis is that the rates supported are discrete as this number is well known and limited. Therefore, it becomes possible to enumerate all possible cooperation scenarios and evaluate their capacity and energy boundaries. More recent amendments to the protocol provide a greater number of transmission modes, however the principles drawn in this work can be applied to any future amendment. All results below were obtained through the popular simulation tool, OMNET++ and using the Mobility Framework.

6.1 Delay and Capacity Performance

In order to show the relay area versus delay ratio using a geometrical representation, we select just the minimum data rate supported by each standard. This corresponds to the situation showing more possibilities of cooperation, or at higher gain. A graphical representation of the geometries for various relay area in IEEE 802.11b, IEEE 802.11g and IEEE 802.11bg standards is depicted in Figure 4, when the end-to-end data rate is the minimum data rates supported in each standard. The color of the spectrum bar indicates the delay ratio achieved: as the delay ratio increases (lighter color), the performance of the cooperation channel decreases.

As shown in Figure 4, IEEE 802.11b presents values of delay ratio between 0.18 and 0.68, whereas in IEEE 802.11g these values vary from 0.45 to 0.91. Cooperation in IEEE 802.11bg experiences values for delay ratio between 0.14 and 0.68. Therefore, IEEE 802.11bg provides the best potential for cooperative relaying. The variation rate of delay ratio in IEEE 802.11bg is more than IEEE 802.11g and IEEE 802.11b, because of more possibilities for cooperation in IEEE 802.11bg compared to the other ones. This means that for wireless network with mobility scenario, the stability of relay nodes with constant delay ratio in IEEE 802.11bg is less than that in IEEE 802.11b and IEEE 802.11g. Figure 5 presents the average value and lower and upper bounds of delay ratio (i.e., AWDR, LBDR and UBDR) for all direct data rates supported by IEEE 802.11b (g and bg) as discussed in Equations (5) to (8). Figure 5(a) shows the delay ratio of those cooperative scenarios leads to a reduction in delay when using IEEE 802.11b (e.g. 1 or 2 Mbit/s). Beneficial values of the delay ratio (< 1) in IEEE 802.11g can be achieved for direct data rates of 6, 9, 12 and 18 Mbit/s (Figure 5(b)) while in IEEE 802.11bg, cooperative communication can be beneficial for direct data rates of 1, 2, 5.5, 6, 9, 12 and 18 Mbit/s. It is worth mentioning that the value of AWDR of some direct data rates in IEEE 802.11bg is lower than the same data rates in IEEE 802.11b and IEEE 802.11g. As an example, AWDR of 1 Mbit/s varies from 0.44 in IEEE 802.11b to 0.4 in IEEE 802.11bg, and the AWDR of 6 Mbit/s also changes from 0.7 in IEEE 802.11g to 0.65 in IEEE 802.11bg. Thus, cooperation in IEEE 802.11bgcan potentially achieve more performance than when using IEEE 802.11b and IEEE 802.11g in terms of delay reduction, and especially for the similar end-to-end direct data rates due to higher number of situations where cooperation is beneficial.

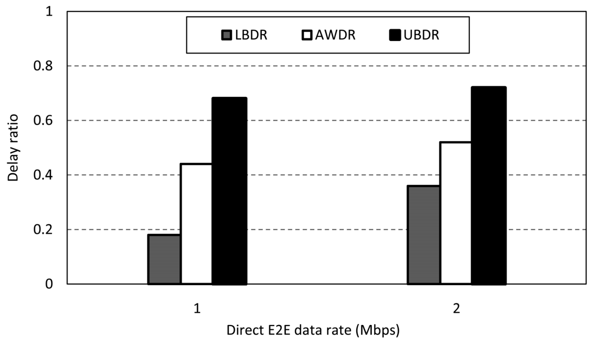
Figure 6 depicts the cooperative capacity in term of average value, lower and upper bounds in IEEE 802.11b (g and bg) as discussed before in Equations (9) to (12). Figure 6 demonstrates that IEEE 802.11bg has a larger capacity improvement of the cooperative channel in relation to IEEE 802.11b and IEEE 802.11g. As is can be seen in Figure 6, the average weighted cooperative capacity (AWCC) has increased by 18% from IEEE 802.11bg to IEEE 802.11b, for an end-to-end data rate of 1 Mbit/s, while it increases by 40% in IEEE 802.11bg when compared to IEEE 802.11b, and for end-to-end data rate of 2 Mbit/s. This will also provide better energy efficiency, as the distance between source and relay is half of the distance between source and destination, thus reducing the power requirements for a successful transmission.

6.2 Energy Efficiency

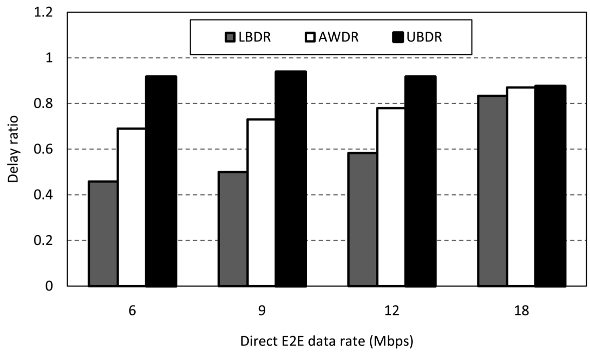
To evaluate the energy efficiency achieved by a cooperative scheme, we select an indoor environment with obstructed communication paths (i.e. a normal building with walls and furniture). The path loss coefficient of this environment varies between 4 and 6 [32]. Table 5 indicates the data set rates which provide the delay ratio close to 1, the value of $\beta = SNR_D - SNR_{Rly}$ and the power gain (PG) as discussed in Section 3. Figure 7(a) presents the power gain obtained for minimum and maximum value of path loss coefficient for data rates supported in IEEE 802.11b and IEEE 802.11g while the delay ratio is close to 1 and we have no throughput improvement. As can be seen from Figure 7(a), in cooperative scenarios, if communicating with a lower data rate, we can achieve higher energy efficiency, when compared to the higher data rate. The energy efficiency of IEEE 802.11b in a cooperative scenario outperforms IEEE 802.11g when the main purpose of cooperation is energy saving with no improvement over throughput. This has to do with the communication range provided by the lowest data rate of both protocols. In the case of IEEE 802.11, this range is much higher, thus leading to a more energy efficiency communication.

In order to find the minimum of path loss coefficient which provide the energy efficiency for the data rate set present in Table 5, we solve the following equation:

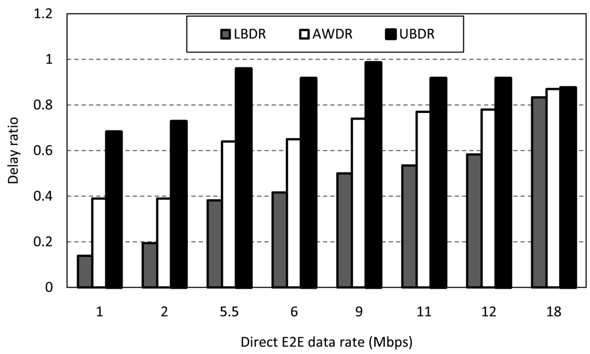
$$PG = \beta + 3(n - 1) \tag{29}$$



(a)



(b)



(c)

Figure 5 Delay ratio: Average value, lower and upper bounds for (a) IEEE 802.11b, (b) IEEE 802.11g and (c) IEEE 802.11bg.

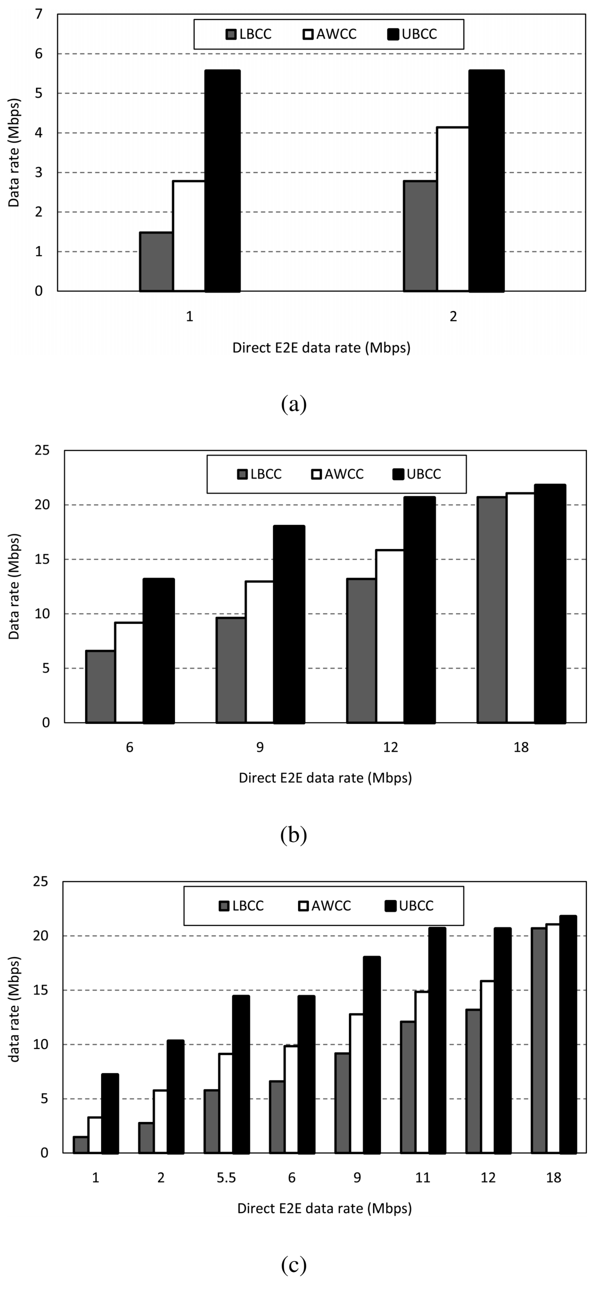
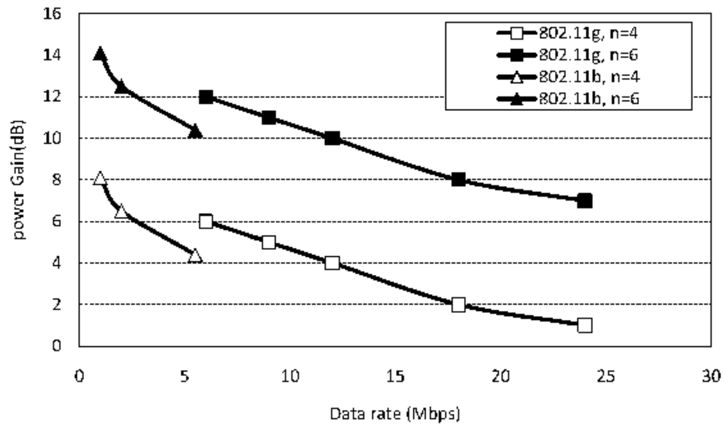
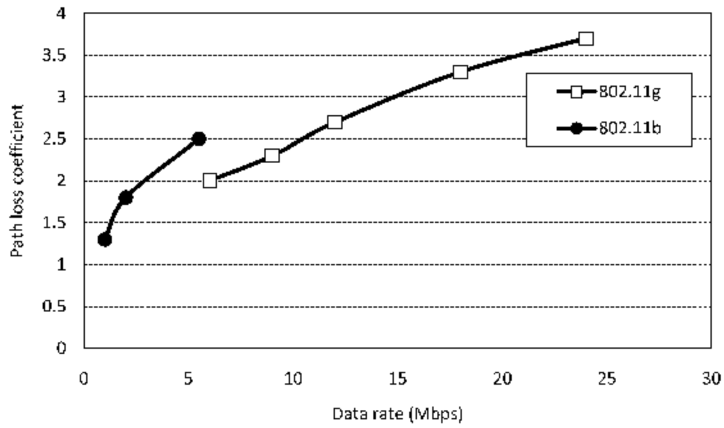


Figure 6 Cooperative capacity: Average value, lower and upper bounds for (a) IEEE 802.11b, (b) IEEE 802.11g and (c) IEEE 802.11bg.



(a)



(b)

Figure 7 Cooperative capacity: Average value, lower and upper bounds for (a) IEEE 802.11b, (b) IEEE 802.11g.

Figure 7(b) shows the minimum of path loss (n_{min}) for every data rate in IEEE 802.11b and IEEE 802.11g. In order to have energy efficiency through cooperative relay based in IEEE 802.11, the environment with smaller value of path loss coefficient can be more beneficial for low data rates. In addition, Figure 7(b) demonstrates that the wireless environment with path loss coef-

Table 5 Data rate set, β and Power Gain (PG) in IEEE 802.11b and IEEE 802.11g.

	Data rate (Mbit/s)	Min (SNR) (dB)	Data rate set			β (dB)	PG (dB)= Min(n = 4) ∼ Max(n = 6)
			SD	SR	RD		
802.11g	6	8	–	–	–	–	–
	9	9	–	–	–	–	–
	12	11	6	12	12	-3	6 ∼ 12
	18	13	9	18	18	–4	5 ∼11
	24	16	12	24	24	–5	4 ∼ 10
	36	20	18	36	36	–7	2 ∼ 8
	48	24	24	48	48	–8	1 ∼ 7
802.11b	1	2	–	–	–	–	–
	2	2.9	1	2	2	–0.9	8.1 ∼ 14.1
	5.5	5.4	2	5.5	5.5	–2.5	6.5 ∼ 12.5
	11	10	5.5	11	11	–4.6	4.4 ∼ 10.4

ficients of more than 2.5 and 3.7 respectively for IEEE 802.11b and IEEE 802.11g can achieve the power gain in cooperative relay scenarios with data rate set as listed in Table 5.

7 Conclusion

In this work, we presented an architectural reference model for cooperative schemes in wireless cognitive networks, called cooperation loop. According to the capabilities of every wireless networks and cooperation purpose, we can draw a spectrum of features for different phases of cooperation loop. As an example, we discussed the cooperation in IEEE 802.11 standards in term of cooperation loop phases. We also present a theoretical analysis for delay performance and capacity improvement of IEEE 802.11.

Simulation results indicate that IEEE 802.11bg outperforms IEEE 802.11b and IEEE 802.11g in term of throughput due to more possibilities for cooperation. We further discussed how energy efficiency values that can be obtained in cooperative scenarios with single relay node and provided guidelines on the environments beneficial in term of energy saving for cooperative IEEE 802.11 standards. Theses guidelines can be included in cognitive algorithms for cooperation decisions, as discussed in our framework. In the future work, we can consider the cooperative strategy and the imposed overhead of some cooperative protocols.

References

[1] M. Cover and A.A.E. Gamal. Capacity theorems for relay channel. *IEEE Transactions on Information Theory*, 25(5):572-584, 1979.

[2] A. Sendonaris, E. Erkipand, and B. Aazhang. User cooperation diversity, Part I: System description. *IEEE Transactions on Communications*, 51:1927-1938, 2003.

[3] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity, Part II: Implementation aspects and performance analysis. *IEEE Transactions on Communications*, 51:1939-1948, 2003.

[4] J. Laneman, D. Tse, and G. Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory*, 50(12):3062-3080, 2004.

[5] P. Liu, Z. Tao, and S. Panwar. A cooperative MAC protocol for wireless local area networks. In *Proceedings of ICC'05*, Vol. 5, pages 2962–1968, 2005.

[6] S. Shankar, C. Chou and M. Ghosh. Cooperative Communication MAC (CMAC) - A new MAC protocol for next generation wireless LANs. In *Proceedings of IEEE International Conference on Wireless Networks, Communications and Mobile Computing*, pages 1–6, 2005.

[7] X. Wang and C. Yang. A MAC protocol supporting cooperative diversity for distributed wireless ad hoc networks. In *Proceedings of IEEE PIMRC'05*, 2005.

[8] A. Sadek, K.J. Ray Liu, and A. Ephremides. Collaborative multiple-access protocols for wireless networks. In *Proceedings of ICC'06*, 2006.

[9] P. Pathak and R. Dutta. A survey of network design problems and joint design approaches in wireless mesh networks. *IEEE Communication Surveys Tutorials*, 2010.

[10] P. Liu, Z. Tao, Z. Lin, E. Erkip, and S. Panwar. Cooperative wireless communications: A cross-layer approach. *IEEE Wireless Communication Journals*, 13(4):84-92, 2006.

[11] H. Shan, W. Zhuang, and Z. Wang. Distributed cooperative MAC for multihop wireless networks. *IEEE Communication Magazine*, 47(2):126-133, 2009.

[12] C. Cetinkaya and F. Orsun. Cooperative medium access protocol for dense wireless networks. In *Proceedings of Third Annual Mediterranean Ad Hoc Networking Workshop (Med Hoc Net)*, pages 197-207,2004.

[13] IEEE, Part 11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifcations, 1999.

[14] M. Heusse, F. Rousseau, G.B. Sabbatel, and A. Duda. Performance anomaly of IEEE 802.11b. In *Proceedings of IEEE Infocom*, Vol. 2, pages 836–843, 2003.

[15] IEEE Std. IEEE 802.11g, Supplement to Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications; Further high-speed physical layer extension in the 2.4 GHz band. 2003.

[16] IEEE Std. IEEE 802.11n, Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications amendment 5: Enhancements for higher throughput, 2009.

[17] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S.S. Panwar. CoopMAC: A cooperative MAC for wireless LANs. *IEEE Journal on Selected Areas in Communications*, 25(2):340-354, 2007.

[18] H. Zhu and G. Cao. rDCF: A relay-enabled mediumaccess control protocol for wireless Ad Hoc networks. *IEEE Transactions on Mobile Computing*, 5(9):1201-1214, 2006.

[19] F. Liu, T. Korakis, Z. Tao, and S.S. Panwar. A MAC-PHY cross-layer protocol for ad hoc wireless networks. In *Proceedings of IEEE WCNC'08*, pages 1792-1797, 2008.

[20] F. Verde, T. Korakis, E. Erkip, and A. Scaglione. On avoiding collisions and promoting cooperation: Catching two birds with one stone. In *Proceedings of IEEE SPAWC*, pages 431-435, 2008.

[21] P. Liu, Y. Liu, T. Korakis, A. Scaglione, E. Erkip, and S.S. Panwar. Cooperative MAC for rate adaptive randomized distributed space-time coding. In *Proceedings of IEEE Globecom'08*, pages 4997-5002, 2008.

[22] P. Liu, C. Nie, E. Erkip, and S. Panwar. Robust cooperative relaying in a wireless LAN: Cross-layer design and performance analysis. In *Proceedings of IEEE Globecom'09*, 2009.

[23] F. Verde, T. Korakis, E. Erkip, and A. Scaglione. A simple recruitment scheme of multiple nodes for cooperative MAC. *IEEE Transaction Communication*, 58(9):2667-2682, 2010.

[24] B. Zhao and M. Valenti. Practical relay networks: A generalization of hybrid ARQ. *IEEE Journal of Selected Areas Communication*, 23(1):7-18, 2005.

[25] S. Cui, A. Goldsmith, and A. Bahai. Energy-effciency of MIMO and cooperative MIMO techniques in sensor networks. *IEEE Journal on Selected Areas Communication*, 22(6):1089-1098, 2004.

[26] R. Ahmad, F.-C. Zheng, and M. Drieberg. Modeling energy consumption of dual-hop relay based MAC protocols in ad hoc networks. In *Proceedings of IEEE ISWPC'09*, 2009.

[27] R. Ahmad, F.-C. Zheng, and M. Drieberg. Delay analysis of enhanced relay-enabled distributed coordination function. In *Proceedings of IEEE VTC'10*, 2010.

[28] J. Kephart and D. Chess. The vision of autonomic computing. *IEEE Computer Journal*, 36(1):41-50, 2003.

[29] J. Mitola. Cognitive radio – An integrated agent architecture for software defined radio. Ph.D. Thesis, Royal Institute of Technology, Kista, Sweden, 2000.

[30] B. Cetin. Opportunistic relay protocol for IEEE 802.11 WLANs. Master Thesis, Royal Institute of Technology, 2006.

[31] T. Rappaport *Wireless Communications: Principles and Practice*. Prentice Hall, 1999.

[32] J. Alonso-Zárate, E. Kartsakli C. Verikoukis, and L. Alonso. Persistent RCSMA: A MAC protocol for a distributed cooperative ARQ scheme in wireless networks. *EURASIP Journal on Advanced Signal Processing*, Special Issue on Wireless Cooperative Networks, 2008.

[33] Rasool Sadeghi, João Paulo Barraca, and Rui L. Aguiar. Metrics for optimal relay selection in cooperative wireless networks. In *Proceedings of IEEE PIMRC'11*, 2011.

[34] Muharrem Ali Tunc. Service differentiation via cooperative MAC protocol (SD-MAC). Master's Thesis, Wichita State University, 2003.

[35] J.S. Pathmasuntharam, A. Das, and K. Gupta. Efficient multi-rate relaying (EMR) MAC protocol for ad hoc networks. In *Proceedings of IEEE ICC'05*, pages 2947-2951, 2005.

Biographies

Rasool Sadeghi is a Ph.D. student in telecommunication engineering, at the MAP-tele program at the University of Aveiro, Portugal. He is also a research member at Instituto de Telecomunicações (IT), Aveiro, Portugal. He has a Master's degree (2004) in Electrical Engineering from Shiraz University, Iran. His current research interests include cooperative and cognitive protocols for MAC protocols in wireless networks.

João Paulo Barraca received the Licenciatura degree in Computers and Telematics Engineering from the University of Aveiro, Portugal in 2004, and two years later a Masters degree in Electronics and Telecommunication Engineering from the same university. He joined Instituto de Telecomunicações in 2003, were he develops his research activities, and in 2008 he became an Invited Lecturer at the University of Aveiro. In 2007 he started pursuing a Ph.D. in Computer Science. His research activities include management mechanisms for community-oriented autonomic networks, and development of experimentation facilities for wireless environments. He has coauthored more than 20 publications, published in journals and conference proceedings.

Rui L. Aguiar received a Ph.D. degree in electrical engineering in 2001 from the University of Aveiro, Portugal. He is currently a professor at the University of Aveiro and an adjunct professor at the INI, Carnegie Mellon University. He is leading a research team at the Institute of Telecommunications, Aveiro, on next-generation network architectures and systems. His participation in European cooperative research is extensive. His current research interests are centered on the implementation of advanced new networks and systems with special emphasis on QoS and mobility aspects. He is a member of ACM and a senior member of IEEE. He has more than 250 published papers in those areas. He has served as technical and general chair of several conferences, such as ICNS'05, ICT'06, ISCC.